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MODEL OF A SIMPLE FAN-RESISTANCE VENTILATION SYSTEM AND ITS APPLICATION TO FIRE MODELING

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Abstract

This paper describes the model FANRES for predicting transport through a simple fan-resistance ventilation system. The system consists of a fan and a duct with a single inlet and outlet. The fan characteristics in the range of normal fan operation and the duct resistance are assumed to be known and specified. Also assumed to be specified are the pressure and density of the environment, and relative elevation local to the two system end-points. The model predicts the system flow rate for arbitrary end-point conditions and can be used to provide an estimate of flow rate even when end-point environments lead to fan operation in the potentially unstable high-head-pressure region of small-positive-flow and small-back-flow. While the model described here is useful generally in the simulation of flow dynamics in facilities with simple HVAC systems, its development was motivated by the need to predict the effects of HVAC systems on compartment fire environments. In particular, the FANRES model was developed for use in zone-type, multi-room compartment fire computer models. Computer fire models which incorporate solutions to FANRES model equations will be capable of simulating fire conditions in facilities with exhaust systems, pressurization systems, cross-flow ventilation systems, and smoke management systems, for example, in shopping malls or atriums. An introduction to zone-type fire modeling is provided, and the FANRES model is

discussed in detail. The effective flow resistance of a system is required as input to the FANRES model. For this reason methods of estimating this resistance are described in some detail.

Key words: air conditioning, atriums, computer models, fans, fire, smoke control, smoke movement, zone modeling.

1. INTRODUCTION

It is generally accepted that fan systems can have a significant influence on fire development and smoke movement. Exhausting smoke from a fire compartment can, to some limited extent, reduce hazard conditions. This approach is used for smoke management in shopping malls and atriums as discussed by Butcher and Parnell (1979) and Morgan and Hansell (1987). In some situations, there is concern that exhaust can influence fire spread and have an adverse effect on firefighting; however, this effect is not well understood.

An effort is underway at the Center for Fire Research of the National Bureau of Standards to study the effects of air handling systems on fire development and smoke spread. One of the products of this effort is a computer model of smoke movement through air conditioning systems (SMACS) developed by Klote (1987). SMACS is a quasi-steady network model capable of simulating smoke transport through complex heating, ventilating, and air conditioning (HVAC) systems with numerous branches, inlets, outlets, and fans. It assumes that the direction of flow throughout the elements of the system are in known, "normal" directions. SMACS has not yet been incorporated in a fire model. One reason for this is that SMACS does not have the capability of simulating the backflow of smoke through portions of an HVAC system ductwork due to fire-generated pressure buildups.

This paper describes a model for simulating flow through a simple fan-resistance system (FANRES) under a wide range of flow conditions, both within and outside a fan's normal range of operation. This model is useful for describing systems which, on the one hand, do not require the multi-node network-type of analysis used by SMACS, but on the other hand, may require estimates of system performance in the region of backward flow where SMACS is not applicable. The FANRES model is uniquely suited for incorporation in multi-room fire models. The specific attributes of the systems to which FANRES is applicable are described later in this paper. While FANRES development was motivated by the need to include the effect of forced ventilation on the analysis of dynamic compartment fire environments, it is a general model that will hopefully find many non-fire-related applications.

The Consolidated Compartment Fire Model (CCFM) development project of the Center for Fire Research at the National Institute of Standards and Technology (formerly the National Bureau of Standards) was a major motivating factor for this work. The CCFM is a zone-type fire model computer code which is being designed to simulate mathematically time-dependent fire-generated environments in complex, multi-room buildings. Its use will enable the simulation of fire phenomena at different levels of modeling detail, from basic to reference or "benchmark," thereby satisfying a wide range of compartment fire modeling needs. CCFM will be well-documented, user-friendly, modular and easily updated. A plan for the development of a generic framework and associated computer software for the CCFM computer code was presented by Forney and Cooper (1987). A prototype application of CCFM has been developed by Cooper and Forney (1987).

In addition to discussing FANRES and providing a general introduction to zone modeling, this paper describes calculation of effective resistances which are needed for input to FANRES.

2. ZONE FIRE MODEL CONCEPT

2.1 Background

Generally, the fire models that have been developed for engineering analysis of smoke transport in buildings can be divided into network models and zone models. Both models use a network of spaces, or rooms, and joining leakage paths, or vents, to represent a building configuration. Network models treat the fire-generated environment in each room of a building as uniform in properties while zone models distinguish in each room a uniform upper layer, the smoke layer, and a lower layer.

Said (1988) has provided a detailed review and comparison of several network fire models that can be used for analysis of smoke control systems.

The common feature of zone fire models is that they describe the bulk of a room's fire-generated environment, away from fire plumes and near-surface boundary flows, as being divided into two uniform-property zones: an upper layer of 'hot' air, heavily contaminated with the fire's products of combustion, i.e., the smoke, and a lower layer of relatively uncontaminated and relatively cool air. Examples of zone models are those by Zukoski and Kubota (1980), Mitler and Emmons (1981), Quintiere, et al. (1981), Cooper (1982), Tanaka (1983), and Jones (1985). A comparison of the various models is beyond the scope of this paper. However, the mathematical framework of each of these models has much in common with the others as is obvious from the review of zone models by Jones (1983). Further, Mitler (1985) compares the features of three of these fire models.

The intent of this section is to provide a simple description of zone models, which will be of help to those unfamiliar with the subject to gain some appreciation of potential of the FANRES model when it is combined with a zone model. It should be realized that each model has its own level of detail and is own unique assumptions in describing mathematically the processes of combustion, heat and mass transfer, and flow dynamics. The following is a

brief generic description of compartment fire phenomena and of the class of zone-type compartment fire models of these phenomena. With regard to a more extensive discussions of the overall phenomena the reader is referred to Cooper (1984) and Kennedy and Cooper (1987) for qualitative aspects and to the above-referenced model references for quantitative aspects.

2.2 Compartment Fire Phenomena

Refer to Figure 1. In a room of fire involvement, air which supports the combustion process is entrained into the combustion zone and mixes with combustion products. There the mixture of gases and fire-generated particulates are heated and driven upward. These materials form a buoyant plume which continues to entrain and mix with air and cool as it rises above the combustion zone to the ceiling. A portion of the energy released from the combustion zone is transferred by radiation to the walls, floor and ceiling. As a result of this, the temperature of these materials begin to increase.

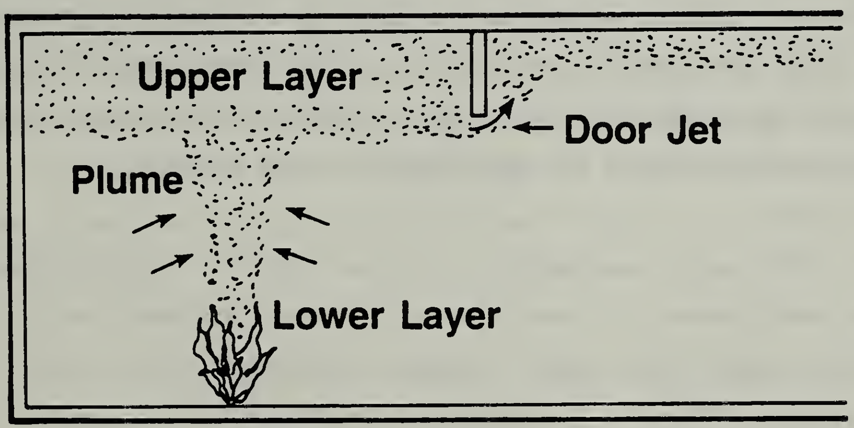

Figure 1. Stratified smoke flow as simulated by zone fire models

As the plume impinges on the ceiling it is redirected outward as a relatively high temperature radial ceiling jet which heats by convection the ceiling surface. Having reached the bounding walls of the room, the buoyant plume gases and particulates eventually redistribute themselves across the entire upper portion of the room and begin to form a relatively quiescent, elevated-temperature smoke layer. As the plume continues to entrain air from the lower portion of the room and to add new material to upper portion of the room the smoke layer grows in thickness and changes in composition.

The interface which separates the upper smoke layer from the lower air layer typically drops eventually below the tops of doors, windows, or other open vents. The smoke then flows out of the fire room and into adjacent rooms or into the atmosphere. At a given vent this outward flow is often exchanged and mixed with inward flowing fresh air. These multi-directional vent flows are driven by room-to-room, cross-vent, hydrostatic pressure differences which vary as a function of elevation and which can change sign one or more times across the vertical extent of a vent.

High temperature smoke which enters an adjacent space is relatively buoyant there and rises to the ceiling by buoyant flow processes which are reminiscent of those discussed above for the fire plume. For example, as illustrated in Figure 1, upper layer gases flowing through a doorway can form an upward flowing door jet, which can begin to form and then add to the growth of an upper layer in an adjacent room. Thus, smoke-filling and -transport is initiated in the adjacent spaces of the facility and beyond.

As mentioned, the major assumption of zone models is that they simulate the fire-generated environment in each room as being divided into an upper, elevated-temperature smoke layer and a lower, relatively-cool, and less-contaminated air layer. This is illustrated in Figure 1.

For simplification, the temperature and composition of each layer is considered homogeneous. In the bulk of the room, away from plumes, vent-flows, and near-surface boundary flows, the environment is relatively quiescent and the pressure, P, is estimated by hydrostatics, i.e., $p = \int g\rho dZ$,

where g is the acceleration of gravity, ρ is the density, and Z is elevation. A Bernoulli-equation formulation of the momentum equation and Z-dependent, cross-vent, pressure differences are used to compute the Z-dependent velocity of room-to-room mass exchanges. Rules for depositing the vent flows into the upper or lower layer of the receiving room are established.

The upper and lower layer of each room is required to satisfy conservation of mass, energy, and species and the equation of state. This leads to a set of time-dependent differential equations in the independent variables. These are the variables which can be used to describe completely the state of both layers, i.e., the overall fire environment, in the room. The equations for all rooms of a simulation taken together form the complete equation set for the model.

The following equations, taken from the CCFM zone model formulation of Cooper and Forney (1987), is an example of a fully-general set of equations for an arbitrary room of a simulation. They are given in the independent variables p, pressure at the floor of the room; V_U, volume of the upper layer; ρ_U and ρ_L, densities of the upper and lower layer; and $c_{i,U}$ and $c_{i,L}$, concentration of product of combustion i in the upper and lower layer. The equations for the dependent variables, T_U and T_L, the temperatures of the upper and lower layers, are also shown. As can be seen below, these are obtained directly from the equation of state of a perfect gas, which is assumed traditionally to be a useful approximation in zone fire model formulations. The complete set of equations is valid when the layer interface is between the floor and the ceiling of the room, i.e., whenever $0 < V_U < V$, the volume of the room.

pressure at the floor of the room:

$$dp/dt = [(\gamma - 1)/V](q_L + q_U)$$

volume of the upper layer:

$$dV_U/dt = [(\gamma - 1)/(\gamma p)][(1 - V_U/V)q_U - (V_U/V)q_L]$$

densities of the upper and lower layer:

$$d\rho_U/dt = (1/V_U)(m_U - \rho_U dV_U/dt)$$

$$d\rho_L/dt = [1/(V - V_U)](m_L + \rho_L dV_U/dt) \tag{1}$$

concentration of product of combustion i in the upper and lower layer:

$$dc_{i,U}/dt = [1/(\rho_U V_U)](M_{i,U} - m_U c_{i,U})$$

$$dc_{i,L}/dt = \{1/[\rho_L(V - V_U)]\}(M_{i,L} - m_L c_{i,L})$$

absolute temperature of the upper and lower layer:

$$T_U = p/(\rho_U R); \quad T_L = p/(\rho_L R)$$

Beside the independent variables and the physical constants γ, ratio of specific heats, and R, the gas constant, the right-hand-side of the above equations depend only on: q_U and q_L, the net rate of enthalpy plus heat transfer plus energy release flowing to the upper and lower layer; m_U and m_L, the net rate of mass flowing to the upper and lower layer; and $M_{i,U}$ and $M_{i,L}$, the net rate of product i flowing to the upper and lower layer. At any instant of time during the course of a fire simulation, the contributions to these terms are dependent on the details of the individual algorithms which describe mathematically the combustion and the various mass and heat transfer processes, e.g., the plume equations, rules for distributing vent flows into the two layers of the receiving room, and the equations for radiative exchanges.

In principle, the above equation set should contain the equation set of any zone-fire model. However, the type and sophistication of the solution

techniques that could be used, whether analytic or, more typically, numeric are not unique. Also, the actual form of (the right hand side of) these equations would depend on the particular details of the collection of algorithms which describe the individual physical phenomena. The CCFM will be relatively flexible with regard to choice of these details. It is being developed in a manner that will allow for a wide range of modeling detail, from basic to "benchmark" simulations.

3. THE FANRES CONCEPT

The FANRES model calculates mass flow rate through a simple fan-resistance system which consists of a fan and resistances such as ducts, bends, dampers. As illustrated in Figure 2, it is assumed that the two endpoints of the system are exposed to two specified and completely arbitrary environments. For the purpose of the present analysis the key properties of these two environments are the pressure and the density, both of which can vary significantly from

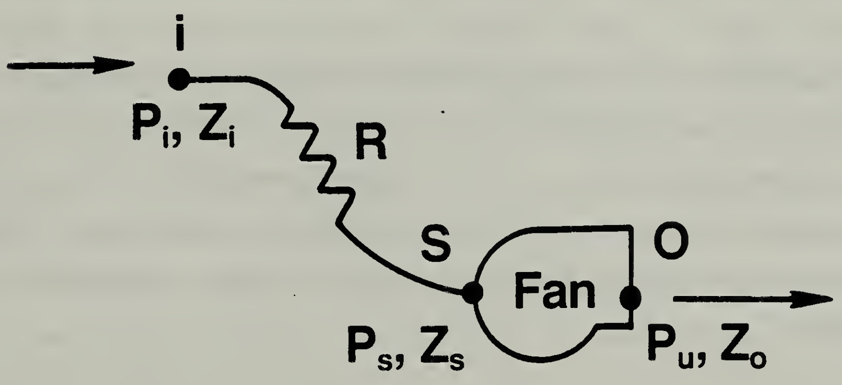

Figure 2. Schematic diagram of a simple fan-resistance system

room-to-room in a multi-room fire environment. Since the analysis will include the possibility of mass flow through the system in either direction, the well-defined conventions on flow direction and density, consistent with Figure 2, are required. The following conventions are adopted: 1) the system endpoints i and o are defined, respectively, as the inlet and outlet to the system under normal fan operating conditions; the mass flow rate, m, is defined as positive if the flow is from station i, the inlet under normal fan operating conditions, to station o, the outlet under normal operating conditions, and negative if the flow is from station o to station i; 3) if m > 0 (m < 0) the density of the flow through the system is uniform and identical to the density specified at station i (station o).

As mentioned, in FANRES the air density is assumed to be uniform throughout the system. It is expected that such an assumption will be reasonable for well-insulated systems with very little heat transfer.

Changes in pressure due to differences in the elevation of the fan inlet, Z_s, and outlet, Z_o, are neglected, i.e., it is assumed that

$$Z_s = Z_o \tag{2}$$

and that all the effects of such elevation differences as well as any fan loss are accounted for in the portion of the analysis pertaining to flow through the effective system resistance. This latter simplification is believed appropriate because, for systems with significant elevation differences, the elevation difference across a fan is generally small compared to that across the entire system.

FANRES calculates the mass flow rate through the fan-resistance system, based on the following input data:

- fan data
- value of the system resistance
- inlet and output elevations, Z_i and Z_o
- inlet and output pressures, P_i and P_o
- inlet and outlet gas densities, ρ_i and ρ_o

When using FANRES in a compartment fire simulation, the first three data items would be constant with time while the latter data, describing the fire-generated environment at Z_i and Z_o, would vary typically during the development of a compartment fire-generated environment.

As illustrated in Figure 3, some potential applications of FANRES are:

- fire in exhausted space,
- fire in pressurized space,
- fire in space with cross ventilation,
- shopping mall and atrium smoke management, and
- smoke transport from one occupied space to another.

Exhausted spaces can include kitchens, toilets, and industrial spaces. Spaces can be pressurized to prevent contamination from the outside, as is done in clean rooms and nuclear reactor control rooms. Cross ventilation is common for many commercial and industrial applications. Atrium smoke management is different from the others in that the fan-resistance system is specifically intended to limit the depth of the smoke layer that accumulates below the ceiling. Applications of a fan-resistance system to mass transfer from one occupied building space to another are uncommon, but they do occur. For example, kitchens and laundries have been 'cooled' with conditioned air that would otherwise have been exhausted. This air can be moved to the kitchen or laundry by a fan-resistance system. Concerns of smoke spread are possibly the reason that such systems are unusual. FANRES will extend the usefulness of zone models by allowing them to be used to simulate the applications discussed above.

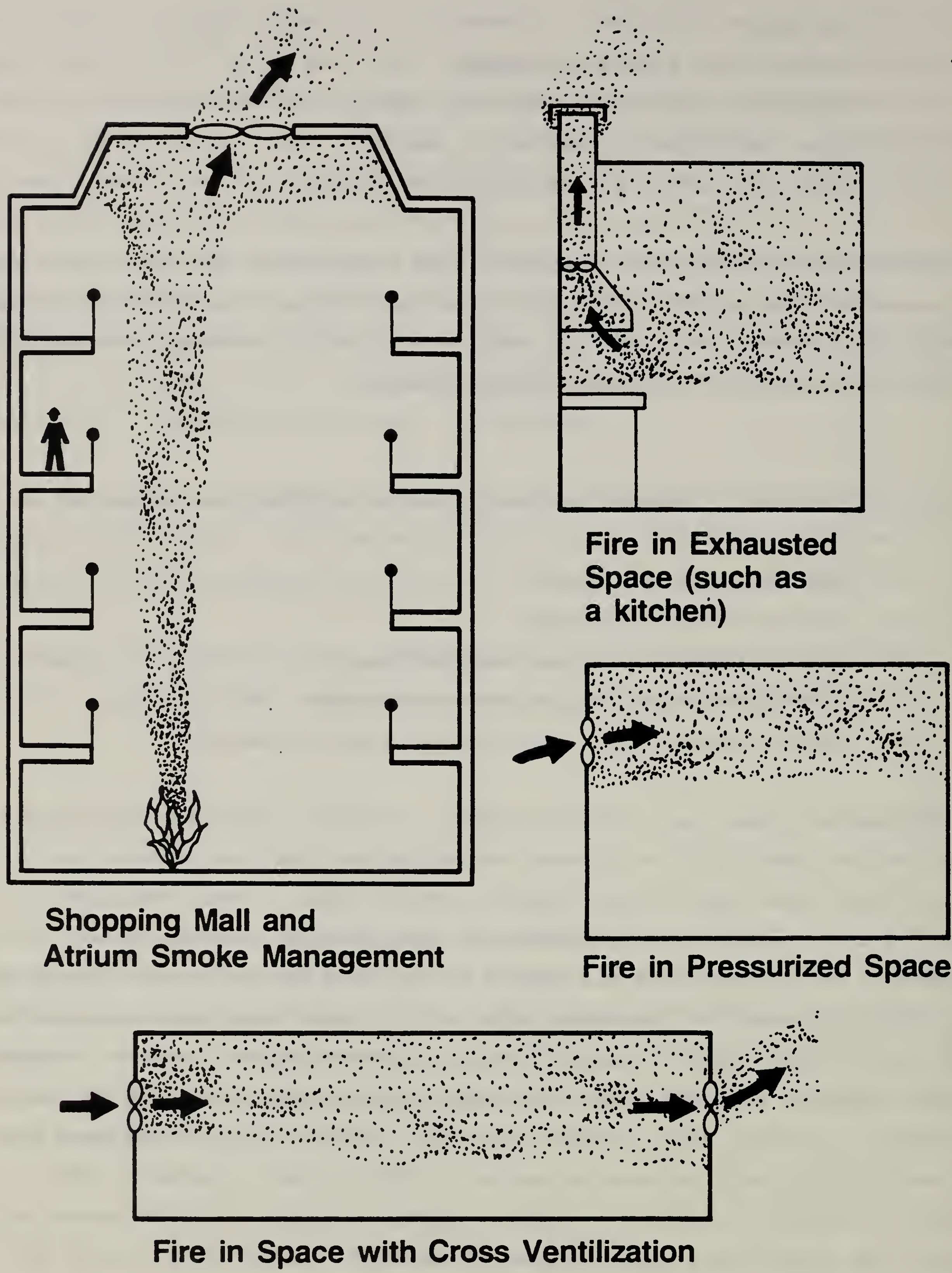

Figure 3. Some potential applications of FANRES in a zone model

In compartment fire model applications, the FANRES model would be incorporated in a zone fire model by using its mass-flow-rate prediction capability to estimate properties of the flowing gas and then the rate of flow of mass, enthalpy, and products of combustion from space i at elevation Z_i and to space o at elevation Z_o. These flow properties and flow rates would then be used to compute the forced-ventilation-system-generated contributions to the q_U, q_L, m_U, m_L, $M_{i,U}$, and $M_{i,L}$ variables on the right sides of Eqs. (1).

The effect of all the resistances in the FANRES system are incorporated in a single effective resistance. The effective resistance of a system of resistances is the resistance that results in the same flow as would occur through the system when each is subjected to the same pressure loss. In Figure 2, the effective resistance is located upstream of the fan. However, FANRES can be used to model systems with resistances located both upstream and downstream of the fan, as discussed later in this paper. For the discussion of FANRES that follows, the resistance is taken to be upstream of the fan with the notation shown in Figure 2. Methods of calculation of effective resistances of a system of many resistances are also discussed later in this paper.

4. THE FANRES MODEL

4.1 Fan Flow

The following description of fan performance is a short digression provided for background information and is based on the handbook Fan Engineering (Jorgensen 1983). The typical performance of a fan operating at constant impeller speed is illustrated in Figure 4. Forcing a fan to operate in the positively sloping portion (CD of Figure 4) of the fan curve results in unstable behavior called surging or pulsation. Unstable flow consists of violent flow reversals accompanied by significant changes in pressure, power, and noise. There is little information about how long a fan can operate in the unstable region before it is destroyed.

Notes:

1. Quadrant terminology is customarily used in descriptions of fan performance. The horizontal axis and the vertical axis divide a plane into four quadrants which for convenience are labeled Q I, Q II, Q II, and Q IV.

2. Forcing the fan to operate in section CD results in unstable behavior called surging or pulsation.
3. Fans are designed to operate in the section AB, and point B is selected with a margin so as to avoid unstable flow.
4. Backward flow occurs in the second quadrant.
5. Fourth quadrant flow is believed to occur for all types of fans. As the ΔP_f becomes negative, the flow increases with decreasing ΔP_f until a choking condition develops at point E.
6. The solid line in the first quadrant indicates the part of the fan curve for which manufacturers generally supply data.

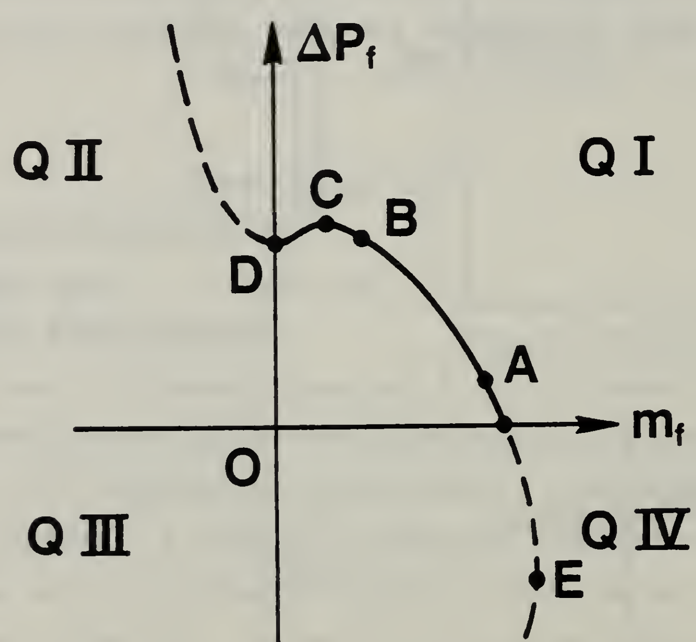

Figure 4. Typical performance of a constant speed fan

Fans are designed to operate in the portion of the curve from ΔP_f of ΔP_{min} to ΔP_{max} (AB of Figure 4), where ΔP_f, the static pressure head of the fan, is

$$\Delta P_f = P_o - P_s \tag{3}$$

and where P_s and P_o are the static pressures at stations s and o, respectively. The maximum pressure head, ΔP_{max}, for normal operation is selected with a margin of safety so as to avoid unstable flow.

Backward flow occurs in the second quadrant (note 1 of Figure 4 explains quadrant terminology) and results when ΔP_f is greater than the shutoff pressure (point D). Backward flow probably is exhibited for all types of fans. The fourth quadrant flow, illustrated in Figure 4, is probably representative of all types of fans. As ΔP_f becomes negative, the flow increases with decreasing ΔP_f until a choking condition develops at point E. Fan manufacturers generally supply pressure-flow data for fan performance for first quadrant operation (Figure 4). However, similar data is not normally available for performance in the second and fourth quadrants.

Because numerical modeling of unstable fan flow is complicated, the fan model used for FANRES does not simulate pulsations. This model, illustrated in Figure 5, simulates m_f, rate of mass flow through the fan in three regions.

In the normal region of fan operation, designated as Region 3, it is assumed that mass flow rate through the fan can be estimated by

<u>Region 3 (the normal region)</u>: $\Delta P_{max} > \Delta P_f > \Delta P_{min} > 0$

$$m_f(\Delta P_f) = \rho V(\Delta P_f) = m_f^{(3)} \tag{4}$$

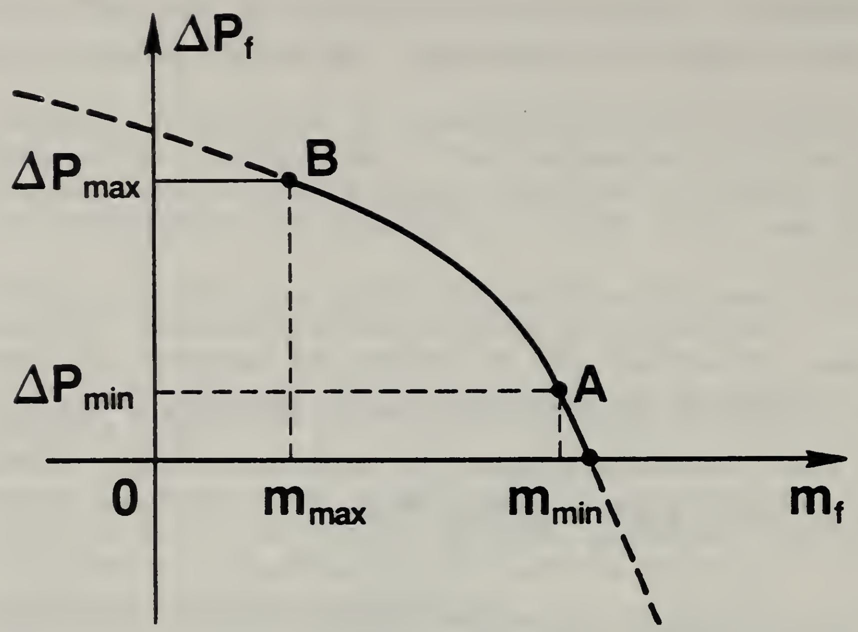

Figure 5. Idealized fan curve used in FANRES

where ρ is the density of the gas flowing through the system and $V(\Delta P_f)$ is a specified function which estimates the volume-flow rate through the fan. As with real fan-flow characteristics, $V(\Delta P_f)$ is required to satisfy $dV/d\Delta P_f < 0$ uniformly in the range $\Delta P_{max} \geq \Delta P_f \geq \Delta P_{min}$.

In Eq. (4), an approximating equation for V with the required first-derivative property would be constructed using fan specifications in the form of a fan curve. This would be provided in graphical or tabular form by the fan manufacturer.

Consistent with Eq. (4), it is common within the industry to represent the fan flow rate, V, as a function of ΔP_f. For incompressible fluids, such flow rates are independent of temperature and pressure. For fan data evaluated at 20 °C, compressibility effects amount to an error of about 6 % at a temperature of 200 °C. For this first order model, compressibility is neglected.

Whatever its functional form, it is assumed that V provides the desired good fit to the manufacturer's fan curve in the normal range. Then define

$$m_{max} \equiv m_f^{(3)}(\Delta P_{max}) = \rho V(\Delta P_{max}) \equiv \rho V_{max} \tag{5}$$

$$m_{min} \equiv m_f^{(3)}(\Delta P_{min}) = \rho V(\Delta P_{min}) \equiv \rho V_{min} \tag{6}$$

For ΔP_f outside of the normal range, m_f is simulated by

<u>Region 1</u>: $\Delta P_f \geq \Delta P_{max} > 0$

$$m_f(\Delta P_f) = m_{max} - \alpha_{max}^2(\Delta P_f - \Delta P_{max}) = m_f^{(1)} \tag{7}$$

<u>Region 2</u>: $\Delta P_f \leq \Delta P_{min} < \Delta P_{max}$

$$m_f(\Delta P_f) = m_{min} - \alpha_{min}^2(\Delta P_f - \Delta P_{min}) = m_f^{(2)} \tag{8}$$

Consistent with Figure 2, $m_f^{(1)}$ and $m_f^{(2)}$ are chosen as the tangent line extensions of $m_f^{(3)}$, where the slope is continuous at $(m_{max}, \Delta P_{max})$ and $(m_{min}, \Delta P_{min})$. Thus

$$\alpha_{max}^2 \equiv -dm_f^{(3)}/d(\Delta P_f)|_{\Delta P_f = \Delta P_{max}} = -\rho dV/d(\Delta P_f)|_{\Delta P_f = \Delta P_{max}} > 0 \tag{9}$$

$$\alpha_{min}^2 \equiv -dm_f^{(3)}/d(\Delta P_f)|_{\Delta P_f = \Delta P_{min}} = -\rho dV/d(\Delta P_f)|_{\Delta P_f = \Delta P_{min}} > 0 \tag{10}$$

α^2_{max} and α^2_{min} are positive because of the guaranteed negative slope of V and $m_f^{(3)}$ at ΔP_f of ΔP_{max} and ΔP_{min}.

It is thought that the Region 2 estimate of Eqn. (8) can achieve an accuracy to within a 10% error at $\Delta P_f = -\Delta P_{max}/2$. However, accurate information about the extent of this error is not available.

Of the three regions of fan operation, the model for the reverse flow portion of Region 1, i.e., when $m_f^{(1)} < 0$ in Eq. (7), is the least reliable. The modeling approach of Eq. (7) is motivated by the requirement that the FANRES algorithm provide a reasonable estimate for the system flow rate under the high head flow conditions where real fan operation is potentially unstable. Thus, FANRES flow estimates in Region 1 allow calculations to proceed in an orderly manner while providing an output flag for appropriate action. In this regard, if FANRES predicts that the fan/resistance system being simulated operates above ΔP_{max} for a relatively short time, the resulting error in the simulated fire environment is likely to be small. However, prolonged operation in this range, especially at predicted regions of backward flow, could lead to significant errors.

While predicted fourth quadrant, Region 2 fan operation is more reliable than a Region 1-type of operation, the concerns of model accuracy are similar. In general, the usefulness of a simulation where the fan is predicted to operate outside of the normal region will be dependent on the particular application. Because of these considerations and because of the limited level of current understanding, it is urged that a degree of FANRES-output-based control of simulation run termination be given to users of fire models which incorporate FANRES calculations.

4.2 Flow Through Resistance

The mass flow through the resistance portion of the system, m_r, is positive or negative depending on whether

$$P_i - P_s + \rho g(Z_i - Z_s) = \Delta P_f + \Delta P_{aj} \tag{11}$$

is positive or negative. Velocity head terms are neglected in Eq. (11). They would cancel for a duct of constant cross-section and density. In the above, ρ is the density of the flow, g is the acceleration of gravity, and

$$\Delta P_{aj} = P_i - P_o + \rho g(Z_i - Z_o) \tag{12}$$

The convention for the direction and sign of m_r is identical to that for m_f. The resistance of the system is defined as the value of R which would provide a reasonable estimate for m_r when calculated in the form

$$m_r = (S/R)(|\Delta P_f + \Delta P_{aj}|)^{1/2} \tag{13}$$

where $S = SGN(\Delta P_f + \Delta P_{aj})$ is +1 or -1 depending on whether $\Delta P_f + \Delta P_{aj}$ is > 0 or < 0, i.e., whether the flow is in the normal or forward direction ($m_r > 0$), or in the reverse direction ($m_r < 0$).

4.3 Conservation of Mass

For quasi-steady flow, conservation of mass at station s of the fan inlet (Figure 2) leads to

$$m = m_r = m_f \tag{14}$$

where m, the uniform mass flow rate through the system, has the same conventions as m_r and m_f. Using Eq. (13), Eq. (14) is rewritten as

$$m = (S/R)(|\Delta P_f + \Delta P_{aj}|)^{1/2} = m_f(\Delta P_f) \qquad (15)$$

where, depending on the region of fan flow operation as determined by ΔP_f, $m_f(\Delta P_f)$ is calculated according to $m_f^{(1)}$, $m_f^{(2)}$, or $m_f^{(3)}$ of Eqs.(7), (8), or (4), respectively.

Eq. (15) is a concise statement of the FANRES problem. The right-hand pair is an equation for ΔP_f. Once this has been obtained, the left-hand pair, for example, yields m directly.

4.4 Graphical Representation of the Solution

Discussion of a graphical solution of Eq. (15) provides insight into the physical operation of the system. For the purpose of this discussion it is assumed that $\rho_1 = \rho_2$.

Figure 6 shows an idealized fan curve and a family of resistance curves, each for different values of P_{aj}. For a particular value of P_{aj}, the intersection of the fan curve and the resistance curve represents the equilibrium point of operation, and the solution of Eq. (15). The term P_{aj} is the pressure difference across the system adjusted for hydrostatic pressure. For P_{aj} of zero, the resistance curve goes through the origin. Generally, a resistance curve through the origin would intersect the fan curve in the region of normal operation (AB of Figure 6). A positive value of P_{aj} indicates that the inlet pressure is relatively high. As is illustrated in Figure 6, this results in an increased flow rate through the system. If P_{aj} is sufficiently large, fourth quadrant fan flow will result. Conversely, a negative P_{aj} results in decreased system flow and possibly even second quadrant flow.

Note:

This figure shows an idealized fan curve and a family of resistance curves, each for different values of P_{aj}. C is an arbitrary constant. For a particular value of P_{aj}, the intersection of the fan curve and that resistance curve represents the equilibrium point of operation, and the solution of Eq. (15).

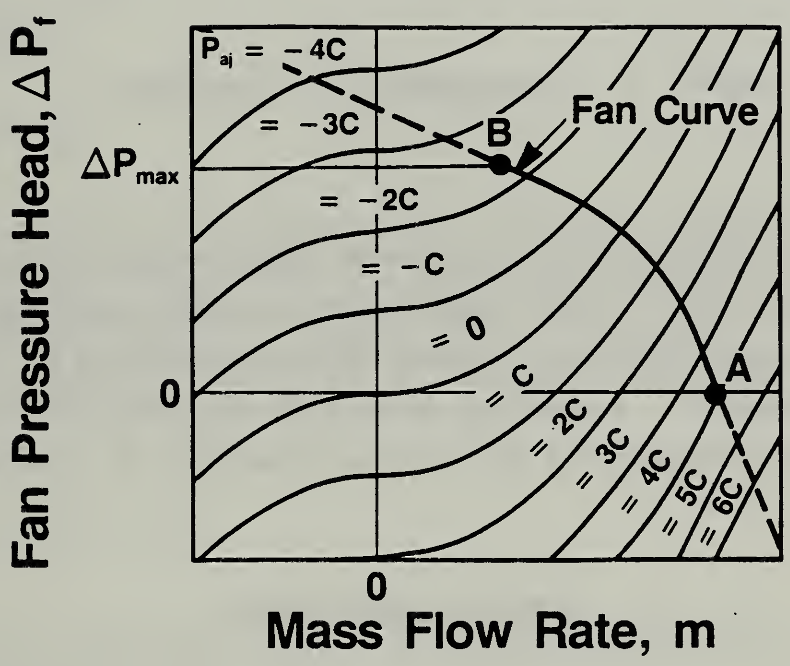

Figure 6. Graphical solution of mass flow through a fan-resistance system

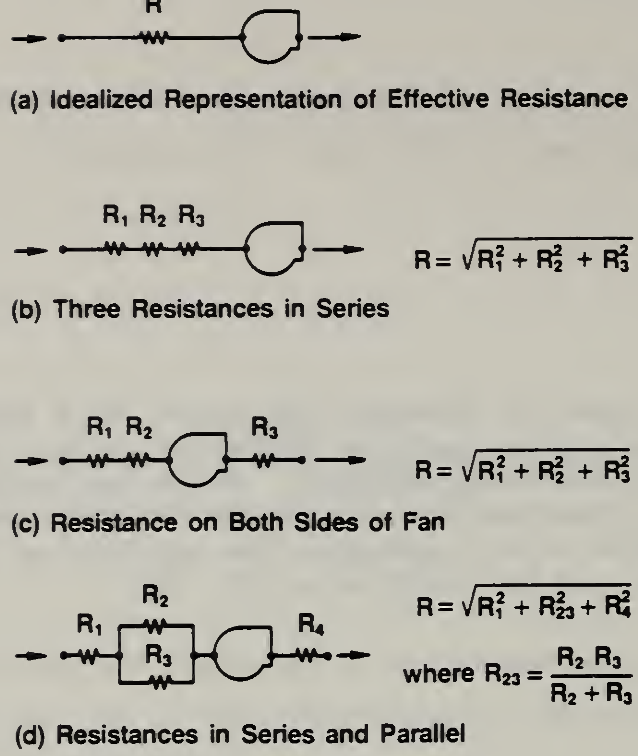

Figure 7. Arrangements of resistances

Eq. (15) is nonlinear, and its solution requires generally a numerical solver. From Figure 6 it is clear that for the assumed condition, $\rho_1 = \rho_2$, unique solutions of Eq. (15) exist for ΔP_f and corresponding m. However, this is not the case generally. A solution to Eq.(15) for arbitrary end-point conditions and system characteristics will be presented in a future paper.

5. EFFECTIVE RESISTANCES

The concept of effective resistance used in the context of this paper is named for a similar concept used in electrical circuit theory. The resistance of an air flow system is made up of numerous elements such as ducts, bends, dampers, coils, inlets, and outlets. Each of these elements contributes to the effective resistance. FANRES does not calculate effective resistances, but, since they are required as parameters in the model equations, information on this subject is supplied here as a convenience to the reader.

At first we will assume that all elevations are the same. Later, a more general approach of choosing different elevations will result in similar equations for effective resistance. Figure 7 shows five different arrangements of resistances, and Figure 7(a) is the idealized case of an effective resistance. The effective resistance, R, of the system is defined as

$$R = \Delta P_r^{1/2}/m_r \tag{16}$$

where ΔP_r is the pressure loss through the effective resistance corresponding to a mass flow rate, m_r.

Referring to Figure 7, the resistance, R_i, of flow element i of the system is defined as

$$R_i = \Delta P_i^{1/2}/m_i \tag{17}$$

where ΔP_i is the pressure loss through the resistance element corresponding to a mass flow rate, m_i. Figure 7(b) is of three resistances in series. The flow through each resistance is the same($m_i = m_1 = m_2 = m_3$). The pressure loss through the effective resistance is the sum of the losses through each element.

$$\Delta P_r = \Delta P_1 + \Delta P_2 + \Delta P_3 \tag{18}$$

Substituting equations (11) and (12) into equation (13), cancelling like terms and rearranging yields

$$R = (R_1^2 + R_2^2 + R_3^2)^{1/2} \tag{19}$$

This equation also applies to resistances on both sides of the fan as

illustrated in Figure 7(c). By similar reasoning, an equation for the effective resistance of N resistances in series can be derived.

$$R = \left(\sum_{n=1}^{N} R_i^{\,2}\right)^{1/2} \tag{20}$$

Parallel resistances are not common in fan-resistance systems, but an example is presented here for completeness. Resistances R_2 and R_3 in Figure 7(d) are in parallel. The pressure drop across each is the same, and the mass flow rate through the effective resistance is the sum of m_2 and m_3 thorough resistances 2 and 3 respectively. Combining this information with the definitions of resistance, the effective resistance, R_{23}, of these two resistances can be expressed as

$$R_{23} = R_2 \cdot R_3/(R_2 + R_3) \tag{21}$$

In Figure 7(d), R_{23} is in series with two other resistances, and the effective resistance of the system is

$$R = (R_1^{\,2} + R_{23}^{\,2} + R_4^{\,2})^{1/2} \tag{22}$$

5.1 Duct Resistance

For a straight section of duct with constant cross sectional area, the Bernoulli equation incorporating pressure loss, ΔP_{loss}, due to friction is commonly written

$$P_1 - P_2 = \Delta P_r = \Delta P_{loss} + \rho g(Z_2 - Z_1) \tag{23}$$

where the subscripts 1 and 2 refer to the duct inlet and outlet respectively, P is pressure, Z is elevation, and ρ is the density of the gas flowing through the system. In the earlier discussion, all pressure drop within the system, ΔP_r, was associated with friction loss whereas Eq. (23) accounts for the hydrostatic pressure drop in systems of non-constant elevation.

The pressure loss due to friction is expressed by the Darcy equation,

$$\Delta P_{loss} = f \cdot (L/D_e) \cdot (\rho U^2/2) \tag{24}$$

where f is the friction factor, L is the duct length, U is the average velocity, and D_e is the effective diameter of the duct. Equations for the effective diameter have been developed for rectangular duct by Huebscher (1948) and for oval duct by Heyt and Diaz (1975). The commonly used hydraulic diameter concept may be used for other geometries. The hydraulic diameter equals four times the cross-section area of the duct divided by the inside perimeter of the duct. An equation for the resistance of a duct can be obtained by combining Eq. (23) and (24) with the definition of resistance and the relation $m = \rho AU$, where A is the cross sectional area of the duct.

$$R = [f \cdot L/(2\rho D_e A^2)]^{1/2} \tag{25}$$

The friction factor is a function of the Reynolds number and the relative roughness of the duct, and it can be obtained from the well known friction factor diagrams reproduced in most elementary fluid dynamics texts. For computer calculations it is convenient to use the Colebrook equation for calculation of the friction factor:

$$f^{-\frac{1}{2}} = -2\log_{10}[\epsilon/(3.7\ D_e) + 2.51\ R_e^{-1} f^{-\frac{1}{2}}]$$

An alternate approach for obtaining the resistance of a duct is to use a duct flow friction chart such as Figure A-1 of Chapter 33 of the ASHRAE Handbook of Fundamentals (1985). From such a chart the pressure loss corresponding to a flow rate can be obtained, and the resistance can be calculated from Eq. (17).

5.2 Other Resistances

Elbows, bends, coils, dampers, filters, duct contractions and expansions, inlets, outlets and other elements have flow resistances that can be described by Eq. (17). The pressure loss, ΔP_r, through these elements can be expressed as

$$\Delta P_r = C_o(\rho U_o{}^2/2) \tag{26}$$

where U_o is the average velocity at cross section o within the element, and C_o is a local loss coefficient. For a large number of these elements, values of C_o have been empirically determined and are tabulated frequently as functions of geometry, for example in handbooks, manuals, etc. such as those published by ASHRAE (1985), the Sheet Metal and Air Conditioning Contractors' Association (1981), and National Environmental Balancing Bureau (Bevirt 1984). The resistance for such an element is

$$R = [C_o/(2\rho A^2)]^{1/2} \tag{27}$$

6. SUMMARY

FANRES is a model which estimates the magnitude and direction of the flow through a simple fan-resistance ventilation system under arbitrary end-point conditions of temperature and pressure. While FANRES is applicable to a wide range of HVAC problems, it was developed explicitly to extend the capabilities of zone fire models by allowing simulation of fire conditions in spaces with exhaust systems, pressurization systems, cross-ventilation systems, and in shopping malls or atriums with smoke management systems. Further, FANRES can be used to model smoke transferred by some simple HVAC systems from one building space to another.

As is common in the fan industry, FANRES simulates fan flow rates with a polynomial function of the static pressure head of the fan for the region of normal fan flow. For flows outside the normal region, FANRES uses linear dependences of flow rate on the static pressure head. Possible significant errors associated with fan flow calculations outside the normal region are a concern, and users of the FANRES model are alerted to this fact.

The flow through a FANRES system would be obtained by solving the model equations which were developed. This would require generally a numerical solution procedure. The effective resistance of ducts, bends, dampers, and other elements of the system required as input to the model. Methods of calculating the effective resistance of a FANRES system which is made up of such elements were presented.

7. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

A	area
C_o	local loss coefficient
c	concentration of a product of combustion
D_e	effective diameter
g	acceleration of gravity
M	product of combustion flow rate
m	mass flow rate
P	absolute pressure
p	absolute pressure at the floor of a room
q	enthalpy flow rate
R	effective resistance or gas constant
R_e	Reynolds number, $R_e = UD_e/\upsilon$

T absolute temperature

U average velocity, $U = m/(\rho A)$

V Volume in Eq. (1) or volume flow rate, Eq. (4)

Z elevation

υ kinematic viscosity

ϵ roughness of the inside surface of the duct

γ ratio of specific heats

ΔP_{aj} pressure difference across a system adjusted for hydrostatic pressure, $P_{aj} = P_i - P_o + \rho g(Z_i - Z_o)$

ΔP_f static pressure head of fan, $\Delta P_f = P_o - P_s$

ΔP_{max} maximum pressure head for normal fan operation

ΔP_{min} minimum pressure head for normal fan operation

ΔP_r pressure loss through resistance, $\Delta P_r = P_i - P_s + \rho g(Z_i - Z_o)$

ρ density

subscripts

f fan

i inlet of fan-resistance system or identifier for a product of combustion

L lower layer

o outlet of fan-resistance system under normal conditions or section o when applied to resistance other that a duct

r resistance

s inlet of fan

U upper layer

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This paper describes the model FANRES for predicting transport through a simple fan-resistance ventilation system. The system consists of a fan and a duct with a single inlet and outlet. The fan characteristics in the range of normal fan operation and the duct resistance are assumed to be known and specified. Also assumed to be specified are the pressure and density of the environment, and relative elevation local to the two system end-points. The model predicts the system flow rate for arbitrary end-point conditions and can be used to provide an estimate of flow rate even when end-point environments lead to fan operation in the potentially unstable high-head-pressure region of small-positive-flow and small-back-flow. While the model described here is useful generally in the simulation of flow dynamics in facilities with simple heating ventilating air conditioning (HVAC) systems, its development was motivated by the need to predict the effects of HVAC systems on compartment fire environments. In particular, the FANRES model was developed for use in zone-type, multi-room compartment fire computer models. Computer fire models which incorporate solutions to FANRES model equations will be capable of simulating fire conditions in facilities with exhaust systems, pressurization systems, cross-flow ventilation systems, and smoke management systems, for example, in shopping malls or atriums. An introduction to zone-type fire modeling is provided, and the FANRES model is discussed in detail. The effective flow resistance of a system is required as input to the FANRES model. For this reason methods of estimating this resistance are described in some detail.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

air conditioning; atriums; computer models; fans; fires; smoke control; smoke movement; zone models

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